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REPORT

NASA CR — 132482

SUBSTANTIATION DATA FOR

ADVANCED BEADED AND TUBULAR STRUCTURAL PANELS

Volume 2, FABRICATION

By

Max D. Musgrove and Russell F. Northrop

THE BOEING COMPANY

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Langley Research Center

Contract NAS1-10749

John L. Shideler Project Manager

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FOREWORD

This report was prepared by the Boeing Aerospace Company, a division of The Boeing Company, Seattle, Washington for the Langley Research Center of the National Aeronautics and Space Administration. The fabrication of advanced beaded and tubular structural element and panel test specimens is presented. The work is part of a comprehensive program to develop advanced beaded and tubular structural panel designs and static strength prediction methods under contract NAS1-10749, "Design and Testing of Advanced Structural Panels". This program was under the cognizance of the contract monitor John L. Shideler, reporting to Herman L. Bohon, head of the Thermal Protection Section of the Structures and Dynamics Division, NASA Langley Research Center.

Manufacturing activities in support of this program were under the direction of Russell Northrop. The technical leader was Max D. Musgrove, reporting to the program manager, John L. Arnquist, Chief of the Structural Methods and Allowables organization.

This report was prepared by Max D. Musgrove and Russell F. Northrop in cooperation with John L. Shideler.

The art work and drafts for this report were prepared by Gary Jensen.

ABSTRACT

A study was conducted to exploit the efficiency of curved elements in the design of lightweight structural panels under combined loads of axial compression, inplane shear, and bending. A summary of the total program (analysis, fabrication and test) is presented in document NASA CR-2514. Detailed descriptions of the analysis effort and of the panel tests are contained in supplementary documents NASA CR-132460 and NASA CR-132515 respectively.

The report presented herein documents the development of economical fabrication techniques to minimize the effects of fabrication limitations on optimum panel designs.

CONTENTS

* Section numbers have been assigned to provide separate section numbers throughout the three substantiating data documents.

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

SUMMARY

A study was conducted to exploit the efficiency of curved elements in the design of lightweight structural panels under combined loads of axial compression, inplane shear, and bending. Governing analytical static strength and stability equations and material and geometric constraint equations were incorporated in a random search type optimization computer program to identify minimum weight designs for several potentially efficient concepts. Buckling tests were conducted on subscale panels to identify local failure modes and provide for modification of local buckling theory where required. Full scale 40 X 40 inch (1 X 1 meter) panels were tested uunder combined loading to obtain failure data for correlation with theory. Modifications to failure theory were made as required. A nondestructive force-stiffness test technique was used in conjunction with the Moire' grid monitoring technique to provide extensive test data from a comparatively few test panels.

A summary of the total program (analysis, fabrication and test) is presented in document NASA CR-2514. Detailed descriptions of the analysis effort and of the panel tests are contained in supplementary documents NASA CR-132460, and NASA CR-132515, respectively.

The report presented herein documents the development of economical fabrication techniques to minimize the effects of fabrication limitations on optimum panel designs. These designs, which can be applied where beaded external surfaces are acceptable aerodynamically or where primary structure is protected by heat shields, offer a favorable cost comparison and 25 to 30 percent weight savings compared to conventional stiffened sheet construction.

INTRODUCTION

For several years the Langley Research Center has been investigating structural concepts which use elements with curved cross sections to develop beaded or corrugated skin panel structure as indicated in References 1 through 6. The curved sections exhibit high local buckling strength which leads to highly efficient structural concepts. These concepts can be applied where a lightly beaded external surface is aerodynamically acceptable or where the primary structure is protected by heat shields. The corrugated nature of the panels makes them especially attractive for high temperature application because controlled thermal growth is permitted which minimizes thermal stress. The technology resulting from this program is applicable to various formable materials and to many areas such as launch vehicles, space vehicles and hypersonic aircraft.

A study was conducted to develop lightweight structural panels for combined loads of axial compression, inplane shear, and bending due to lateral pressure. (See Reference 7.) Governing analytical static strength and stability equations for panels under combined load, and material and geometric constraint equations were incorporated in a random search type optimization computer program described in Reference 8 to identify minimum weight designs for several potentially efficient concepts. However, in order for these concepts to realize their analytical potential, all of the significant failure modes had to be properly recognized and accounted for. Consequently, a major fabrication and test development effort was initiated. Buckling tests were conducted on subscale panels to identify local failure modes and provide the modification of local buckling theory where required. Full scale 40 x 40 inch (1 x 1 meter) panels were tested under combined loading to obtain large panel failure data for correlation with theory. A non-destructive force-stiffness test technique described in Reference 9, was used in conjunction with the Moire' grid monitoring technique to provide extensive test data from a comparatively few test panels.

A summary of the total program (analysis, fabrication, and testing) is presented in document NASA CR-2514. Detailed descriptions of the analysis effort and of the panel tests are contained in supplementary documents NASA CR-132460 and NASA CR-132515, respectively.

The report presented herein documents the development of economical fabrication techniques to minimize the effects of fabrication limitations on optimum panel designs. These designs, which can be applied where beaded external surfaces are acceptable aerodynamically or where primary structure is protected by heat shields, offer a favorable cost comparison and 25 to 30 percent weight savings compared to conventional stiffened sheet construction.

21.0 BACKGROUND

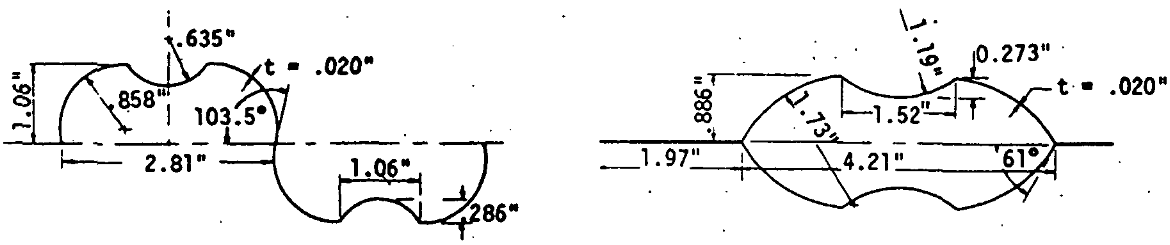
Many recent high performance vehicle designs, such as the space shuttle orbiter, employ large thick low aspect ratio wings which are lightly loaded. Investigations indicated in Reference 4 have shown that tubular panels designed for loads in this range are 25 to 30 percent lighter than conventional stiffened panels.

Prior studies of beaded and tubular structural panels by The Boeing Company indicated that close control of material thickness would be required in order to realize the desired structural efficiencies. Therefore, plans to exploit the potential of curved elements in beaded and tubular panels required the development of fabrication techniques to provide the maximum versatility in bead geometry and geometry control while eliminating material thinning.

It was necessary to select a structural material, a panel size and specific load combinations for use in comparing the different panel configurations. 7075-T6 aluminum was selected to provide a high proportional limit (thus allowing panel designs with high elastic stress) and ease of fabrication. A panel size of 40 x 40 inches with the beads terminated at the supports and two specific loading combinations were selected as typical of lightly loaded wing design.

The selected loading conditions were: (1) 600 lb/in. axial compression, 200 lb/in. inplane shear and 1 psi lateral pressure, and (2) 2000 lb/in. compression, 400 lb/in. shear and 2 psi pressure. These are referred to as design load conditions (1) and (2), or low load and high load, respectively. Only room temperature conditions were considered.

The bead and tube cross section designs selected for fabrication are shown in Figure 21-1. Configurations (1A-1) and (2A-1) are designed for load condition (1) and (2-2) and (2A-2) for load condition (2). Analysis and rationale which led to these selections are presented in References 7 and 8.

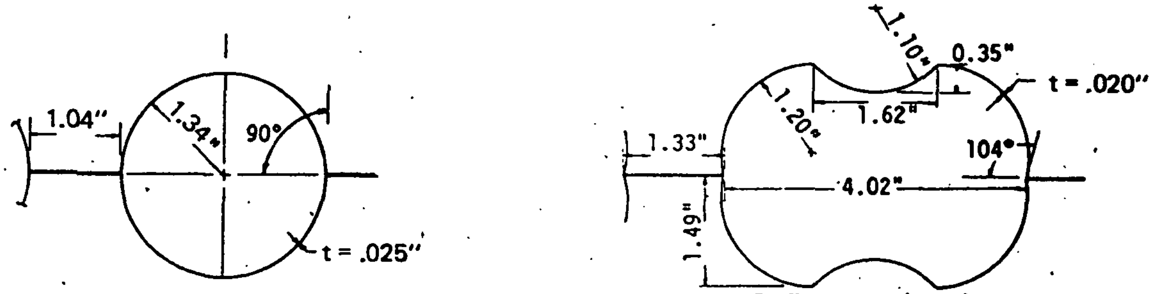


FLUTED SINGLE SHEET (1A-1)

FLUTED TUBE (2A-I)

PREDICTED PANEL STRENGTHS

FLUTED SINGLE SHEET (1A-1)	FLUTED TUBE (2A-I)
N_X = 558 LB/IN	N_X = 498 LB/IN
N_{XY} = 186 LB/IN	N_{XY} = 166 LB/IN
p = 1.0 PSI	p = 1.0 PSI



CIRCULAR TUBE (2-2)

FLUTED TUBE (2A-2)

PREDICTED PANEL STRENGTHS

CIRCULAR TUBE (2-2)	FLUTED TUBE (2A-2)
N_X = 1791 LB/IN	N_X = 1685 LB/IN
N_{XY} = 358 LB/IN	N_{XY} = 337 LB/IN
p = 2.0 PSI	p = 2.0 PSI

Figure 21-1 OPTIMUM PANEL DESIGNS AS MANUFACTURED

21.1 Conventional Trapped Bead Forming

The conventional forming approach for beaded panels is a single stage operation with all of the beads in a single panel formed simultaneously. This approach, or type of forming, is referred to as trapped-bead forming where the total bead configuration is produced by stretching which often results in undesirable thickness variations. Several processes can be used to form the trapped bead configuration, such as hydroform (trapped rubber or Guerin process) impact-forming, matched-die press-forming and high-energy-rate forming. Staging, or reforming, can be applied to deepen the bead and reduce thickness variations. However, this forming approach is restricted by the uniform elongation limit of the specific alloy, and extensive tooling development is required to minimize thickness variations. Both the bead depth and the material thinning limitations can contribute to reductions in the resultant structural efficiency.

21.2 Incremental Brake Forming Technique

Alternate methods of forming were investigated to determine a method which would avoid the limitations associated with conventional trapped bead forming. It was found that incremental forming would permit fabrication of uniform bead or corrugation cross sections of virtually any desired configuration.

The incremental forming process which was developed for producing the uniform cross-section is a brake-forming operation which induces no significant stretching or thinning of the workpiece. The beads are formed full length as single elements, allowing free draw on both sides of the bead centerline. Investigations also indicated that the corrugated sheets could be reformed using relatively simple tooling to form bead ends at the ends of the panel.

This fabrication technique offered both greater versatility in configuration selection and better configuration control than the various trapped bead forming processes.

21.3 Comparative Fabrication Costs

A comparison of the major costs associated with the two fabrication techniques considered, hydro-forming and brake forming is presented. The factors which affect the unit fabrication costs include; (1) direct labor required for fabrication, (2) labor and material required to fabricate the forming tools, and (3) the number of units being produced. Factors which in turn affect these include the panel size and shape and the number of panels required of a given design.

A breakdown of the direct labor charges for fabrication of the initial 40 x 40 inch tubular panel is shown in Table 21-1. The initial tooling costs were similarly developed. Initial costs and an assumed 50% learning curve were used to develop unit panel costs including direct labor and prorated tooling costs. The assumed curve indicates that the direct fabrication labor will decrease to 50% of that required for the first panel by the 100th panel and remain constant thereafter.

Figure 21-2 compares the unit costs for fabricating 40 x 40 inch tubular aluminum panels. It shows that the tool cost dominates for a small number of panels but the direct cost controls for a large production run. This figure also shows that the unit cost is least for the brake formed panels for sets of fewer than 70 panels per set of dies although the difference in cost for the two forming techniques is relatively small.

Table 21-1: BEADED PANEL FABRICATION OPERATIONS

40 x 40 PANEL

OPERATION	DIRECT HOURS
STRETCH FORMED PANELS	
• Shear Panel (7075-0)	0.5
• Shear Picture Frame Doublers	0.5
• De-burr	0.5
• Clean	0.5
• Spot-weld Picture Frame to Doublers	3.0
• Form 1st Stage	2.0
• Form 2nd Stage	2.0
• Clean	0.5
• Solution Heat Treatment	0.5
• Form 3rd Stage	2.0
• Rough Trim	0.5
• De-burr	0.5
• Clean	0.5
• Assemble/Age	3.5
• Net Trim	0.5
• Clean	0.5
	18.0
	* 2.0
	20.0
BRAKE-FORMED PANEL (40 x 40)	
• Shear Panel (7075-0)	0.5
• Drill Index Holes (24 places)	2.0
• Blank Cut-outs	2.0
• De-burr	4.0
• Clean	0.5
• Solution Heat Treatment	0.5
• Form Bead	4.0
• Form Closure	4.0
• Straighten	1.5
• Rough Trim	0.5
• De-burr	0.5
• Clean	0.5
• Assemble/Age	3.5
• Net Trim	0.5
• Clean	0.5
	25.0
	* 2.0
	27.0
*** COMMON TO BOTH PANELS (PREPARED DOUBLERS)**	
• Shear Doubler Blanks	0.5
• Blank Doublers	0.5
• De-burr	0.5
• Clean	0.5
	2.0

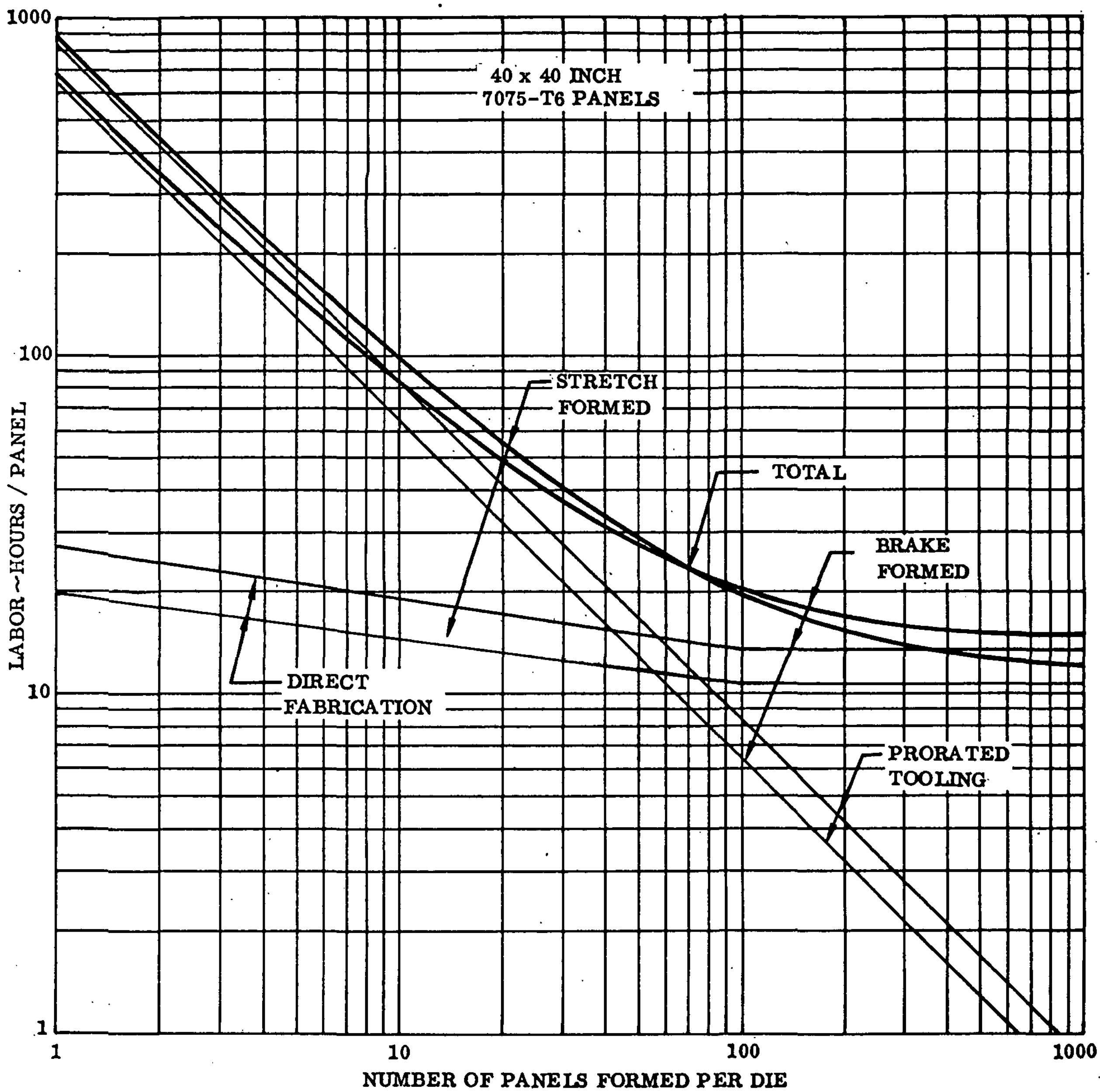


Figure 21-2: BEADED PANEL FABRICATION LABOR VERSUS NUMBER OF PANELS

22.0 FORMING TECHNIQUE DEVELOPMENT

Development of the panel designs and the associated fabrication techniques was an evolutionary process. Selection of the uniform section designs was accomplished by analytical processes while the development of end closure designs and the fabrication techniques has been a fabrication, test and modification process. The approach proved to be rapid, economical and reliable.

22.1 Uniform Section Tooling

The equipment used to form the uniform panel sections consisted of standard brake forming presses plus a set of special dies for each different bead configuration. Figure 22-1 shows one of the circular tube panels being brake formed. Figures 22-2 and 22-3 show the motion of the dies in the process of forming one circular arc section. Although the circular tube design requires only 180 degree bead arcs the material springback in the 0.025 inch sheet necessitated the use of dies with an arc in excess of 180 degrees. This in turn necessitated the use of the two part female die. A strip of rubber located under the center of the die holds the die open as shown in Figure 22-2 and permits it to close as shown in Figure 22-3.

Figure 22-4 shows the springback curve that was developed by test and used to support the design of the various brake forming dies. As indicated in Figure 22-4 the curve was developed for the material in the W condition and the parts were all formed in that condition. It was necessary to empirically develop similar springback curves for each thickness of panel fabricated for this program.

Figure 22-5 is a photograph of the end of a circular tube panel which shows that the bend radius at the juncture of the bead and the flat was increased to approximately 10t at the end of the panel. This was done to permit the end closures to be reformed without memory of the original mold line.

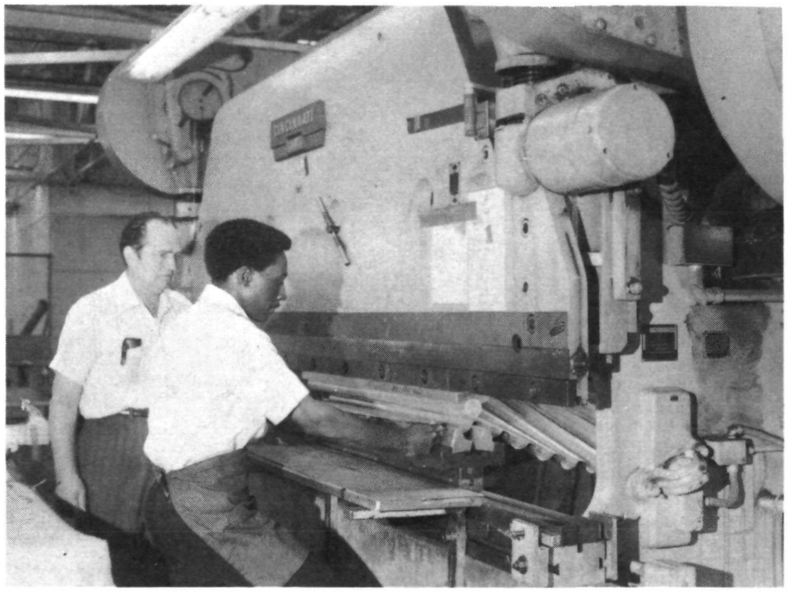


Figure 22-1: BRAKE FORMING IN STANDARD BRAKE MACHINE

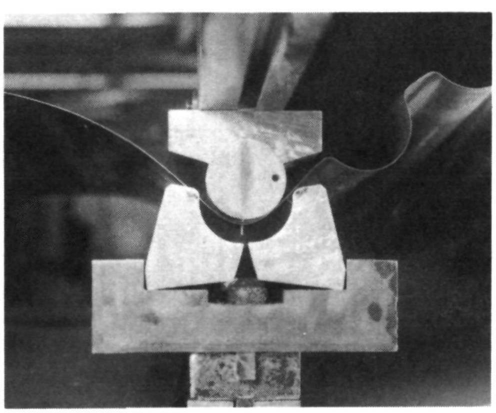


Figure 22-2: UNIFORM SECTION BRAKE FORMING —DIE OPEN

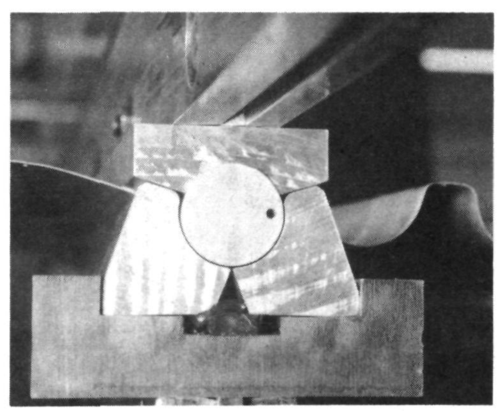


Figure 22-3: UNIFORM SECTION BRAKE FORMING —DIE CLOSED

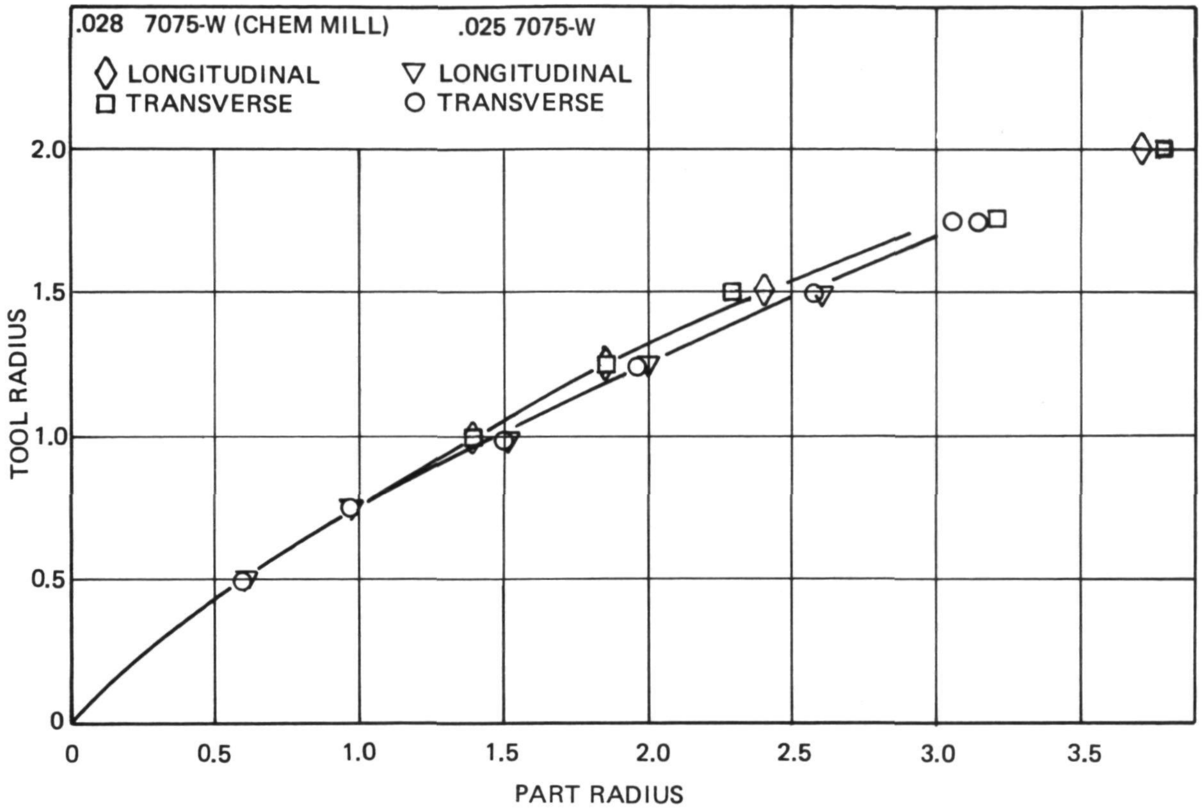


Figure 22-4: 7075 ALUMINUM SPRINGBACK CURVES

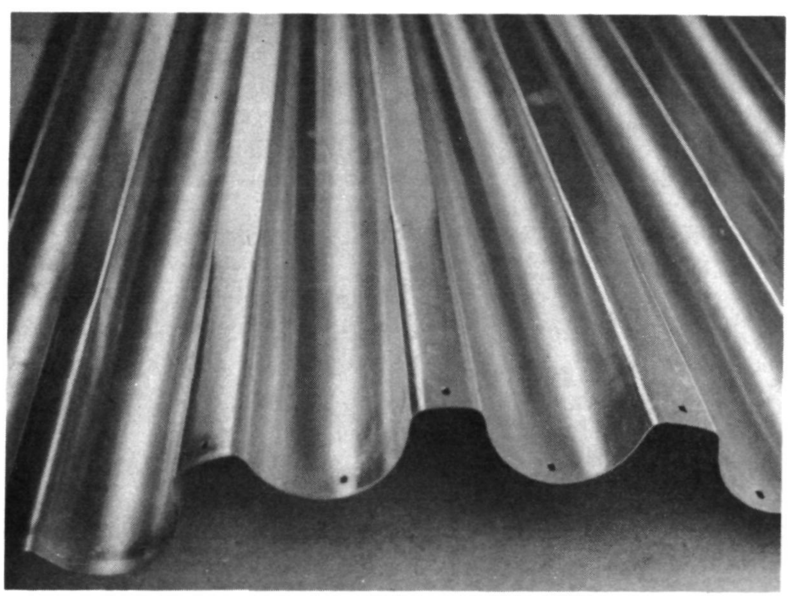


Figure 22-5: CIRCULAR TUBE PANEL FACE SHOWING INCREASED FORMING RADIUS AT ENDS

Uniform sections of the fluted single sheet and the fluted tube designs were formed using appropriate shaped dies and similar techniques.

The high load fluted tube panels were the most complex of the four designs to form. Three separate brake form dies were required in order to develop the required cross-section, as indicated below. Figure 22-6 shows the blank being placed in the initial forming die after one bead has been formed. Figure 22-7 shows the part being placed in the die for final shaping of the flute and Figure 22-8 shows the part being positioned for the final bend at the bead-to-flat intersection. Figure 22-9 shows a brake formed part being checked with a template. Dimensions of the formed sheets were considered acceptable within manufacturing tolerances. However, actual measured dimensions were used in the analysis for correlation with test results as described in Reference 8.

22.2 End Closure Evolution

The end closure design evolution included a number of fabrication and evaluation cycles. The first cycles included very simple specimens which served only as models for further design improvements. Later specimens in the evolution process were tested under various load conditions to determine what additional design improvements should be made. A description of that evolutionary process is presented below.

22.2.1 Single Sheet End Closures

Figure 22-10 shows the first specimen that was fabricated to illustrate the concept of a developable bead with the bead flattened at the end. Figure 22-11 shows the first beaded specimen with curved elements. Figure 22-12 shows the first tubular specimen which was fabricated using the dies that were used in fabricating the specimen shown in Figure 22-11. The specimen shown in Figure 22-12 was chem milled to provide reinforcement in the end attachment. Figures 22-13 and 22-14 show early end closure specimens that were formed using the first tapered end closure forming die. The tapered end closures were necessary in order to provide adequate transfer of the

Figure 22-6: ***BRAKE FORMING INITIAL TUBE IN HIGH LOAD FLUTED TUBE PANEL FACE***

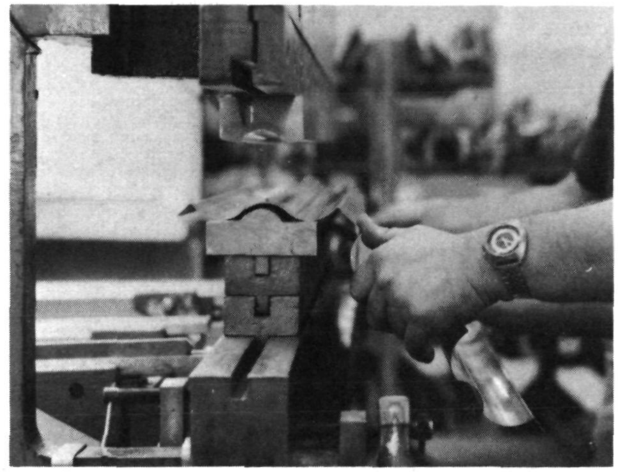


Figure 22-7: ***BRAKE FORMING FLUTE IN HIGH LOAD FLUTED TUBE PANEL FACE***

Figure 22-8: ***BRAKE FORMING FINAL BEND AT BEAD-TO-FLAT INTERSECTION***

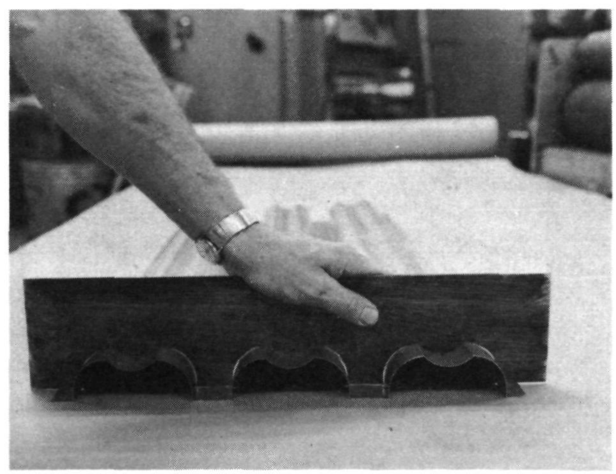


Figure 22-9: ***CHECKING HIGH LOAD FLUTED TUBE SECTION WITH TEMPLATE***

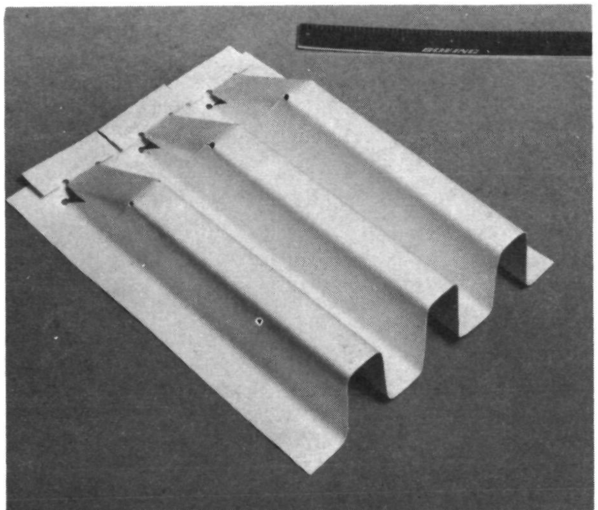


Figure 22-10: FIRST END CLOSURE CONFIGURATION

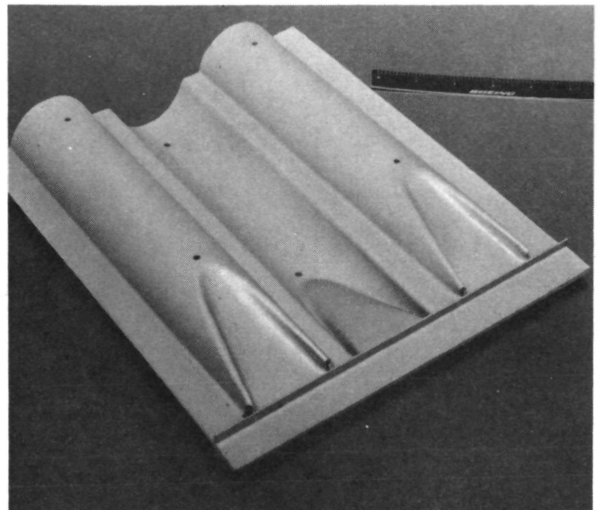


Figure 22-11: FIRST BEADED SPECIMEN WITH CURVED ELEMENTS

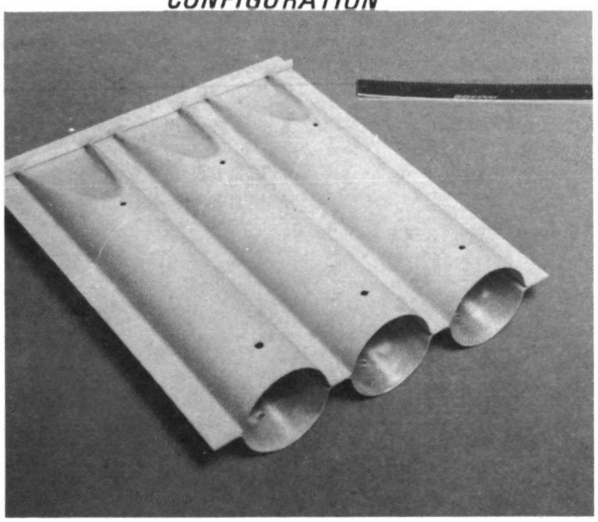


Figure 22-12: FIRST TUBE SPECIMEN

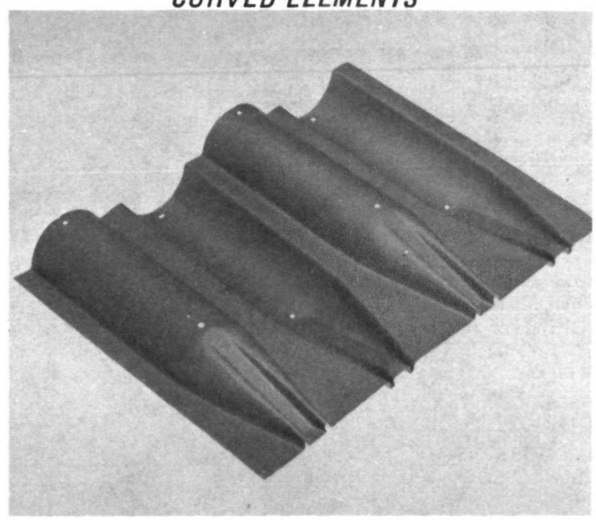


Figure 22-13: EARLY END CLOSURE WITH FLAT

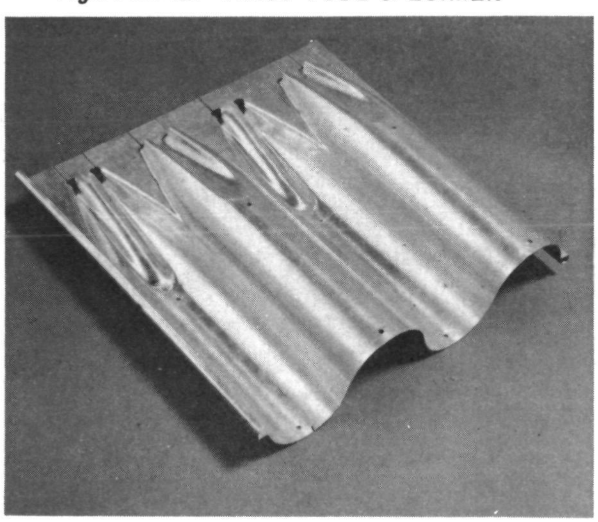


Figure 22-14: EARLY END CLOSURE WITHOUT FLAT

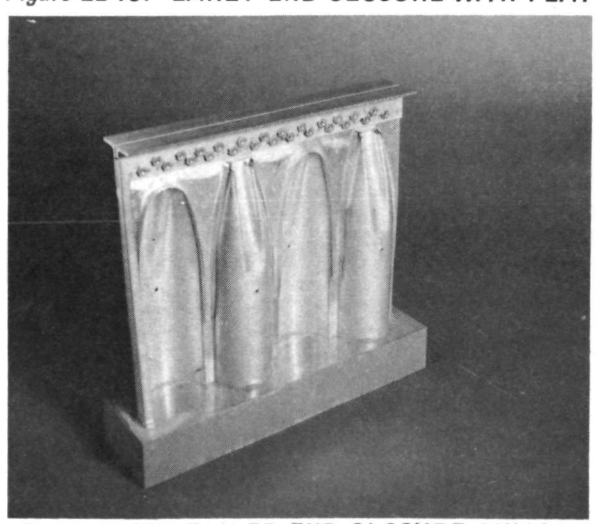


Figure 22-15: FAILED END CLOSURE AXIAL COMPRESSION TEST SPECIMEN

loads from the end attachments to the uniform section. Figure 22-15 shows a failed compression test specimen which was found to have inadequate continuity of stiffness between the end closure and the end attachment. Specimens of this type also displayed excessive distortion in the area of the end closure when loaded in shear. Specimens of the type shown in Figures 22-16 and 22-17 were fabricated in an attempt to obtain improved stiffness at the end of the end closure. When prepared with proper end attachments and loaded these specimens developed adequate axial compression strength but they displayed excessive out-of-plane distortions when loaded in shear. The filler blocks used in the end closures also constituted an undesirable weight penalty.

Subsequent to the above tests, end closures of the type shown in Figure 22-18 were conceived in an attempt to eliminate the above problems. The specimen shown in Figure 22-18 is also different than the compression test specimen shown in Figure 22-15 in that it has relatively heavy "T" shaped chord members along the sides of the test specimen to stabilize the edges. Compression test specimens with the formed bead end closures of this design did carry axial compression load quite adequately. However, when loaded in shear and monitored with Moire' grid and strain gages, excessive out-of-plane bending strains and deflections were again observed as indicated in Figure 22-19. In this instance the Moire' lines are obtained by placing cut pieces of gridded glass immediately adjacent to the surfaces between the beads. The observed out-of-plane deflections are caused by local couples which result from a transition of the local shear center for the individual beads where the beads are closed out. In the center of the panel the local shear center is located outside of the contour of the bead. However, in the end attachment area the shear center is at the center of the sheet. These out-of-plane deflections result in reduced shearing stiffness and undesirable stress concentrations.

Figure 22-20 shows a specimen that is identical to that shown in Figure 22-19 with the exception that two short "T" sections have been attached to each side of the specimen. The Moire' grid indicates that the out-of-plane deflection problem was not eliminated. Figures 22-21 and 22-22 show two additional designs that were fabricated and tested with no success in eliminating the out-of-plane deflections associated with the single sheet beaded specimens loaded in shear.

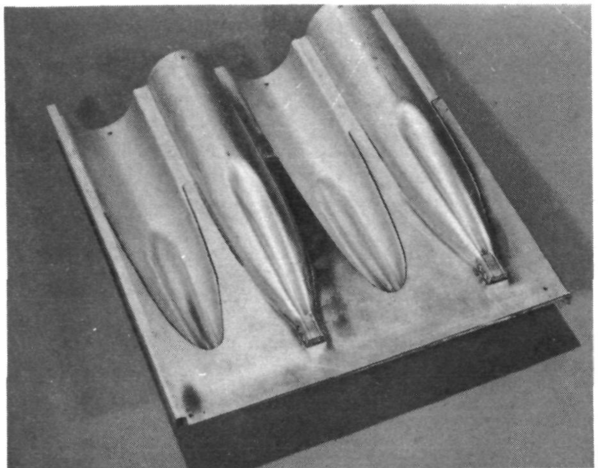


Figure 22-16: *EARLY END CLOSURE WITH FLATS BETWEEN BEADS*

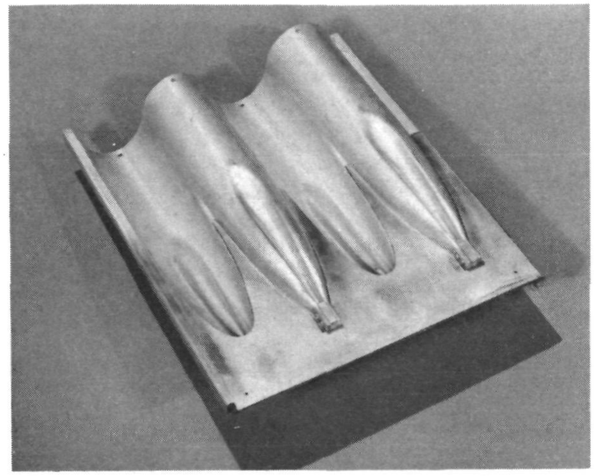


Figure 22-17: *EARLY END CLOSURE WITH NO FLATS BETWEEN BEADS*

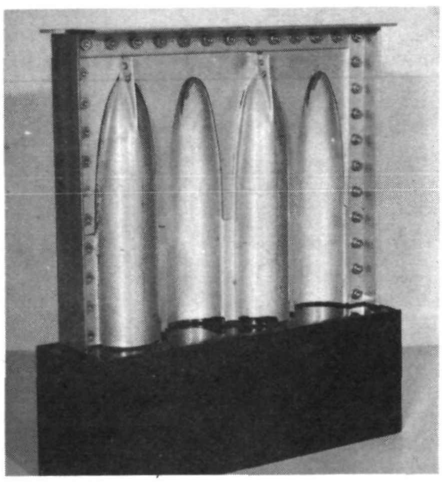


Figure 22-18: *SINGLE SHEET END CLOSURE SHEAR TEST SPECIMEN*

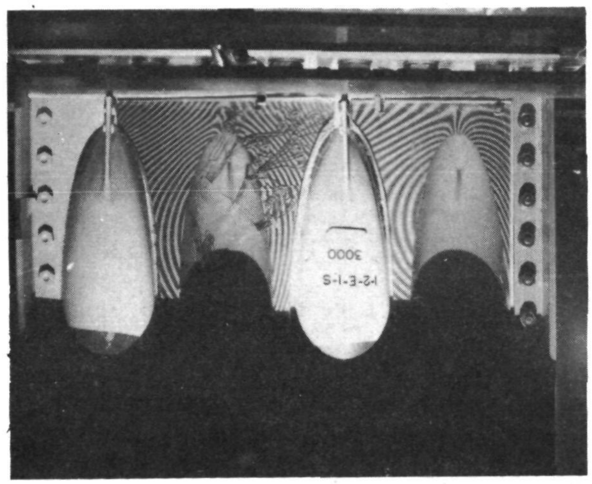


Figure 22-19: *MOIRE PHOTOGRAPH OF SINGLE SHEET END CLOSURE LOADED IN SHEAR*

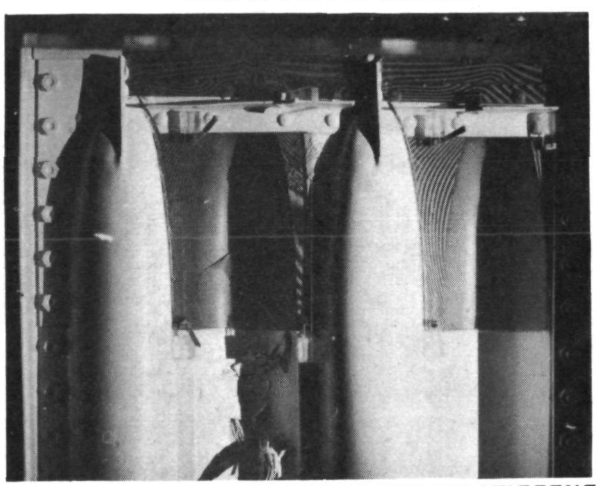


Figure 22-20: *MOIRE PHOTOGRAPH OF STIFFENED SINGLE SHEET END CLOSURE LOADED IN SHEAR*

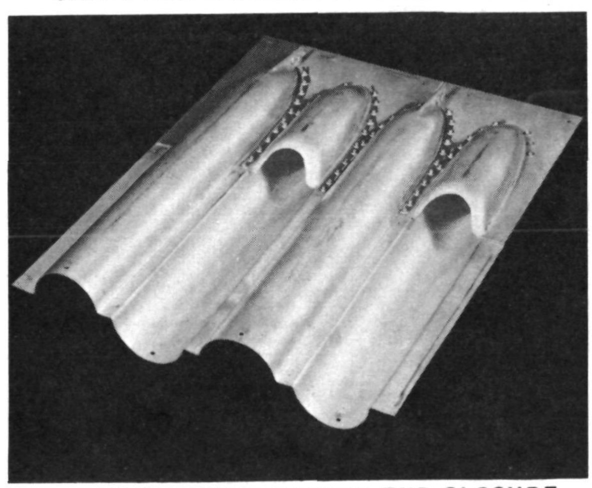


Figure 22-21: *SINGLE SHEET END CLOSURE DEVELOPMENT SPECIMEN*

Figure 22-23 shows the last end closure specimen that was fabricated in an attempt to eliminate the out-of-plane deflection problem. This specimen makes the shift in the local shear center at a location farther from the end of the bead and it maintains a larger portion of out-of-plane bending stiffness of the bead side wall to the end of the joint splice member. However, the Moire' grid lines seen in Figure 22-24 indicate that the out-of-plane deflection problem was not eliminated.

The inability to eliminate the single sheet end closure out-of-plane deflection problem resulted in the decision to employ some other technique in order to test the fluted single sheet panels. Figure 22-25 shows a fluted single sheet shear test specimen with the type of attachment that was used in testing the corresponding panels. The end chord or cap was fabricated from a thick aluminum plate. First, a strip of copper was formed to the shape of the corrugated sheet. The copper strip was then used as the electrode for electrical discharge machining of a corresponding groove in the aluminum plate. The copper electrode was also used as the tracing template for removal of the excess portion of the plate in a Hydro-tel milling machine. Finally the plate was attached to the corrugated sheet test specimen by bonding. The specimen was tested in both compression and shear to loads well in excess of the predicted strengths for the 40 x 40 inch (1 X 1 m) panels, thus substantiating the design for use with the full size panels.

22.2.2 Circular Tube End Closures

The two sheet end closure development proceeded simultaneously with the single sheet development using the same forming dies in many instances. Figure 22-26 shows a Moire' grid photograph of a two sheet end closure specimen that was fabricated using the same dies used in forming the single sheet initial screening configuration specimens shown in Figures 22-18 through 22-22. The Moire' lines indicate a bond peel failure that occurred at a shear load approximately equal to the value which was predicted as the pure shear load strength of the full size panels. The forces driving the bond peel failure in the two sheet specimens were the same as those driving the out-of-plane deflections in the

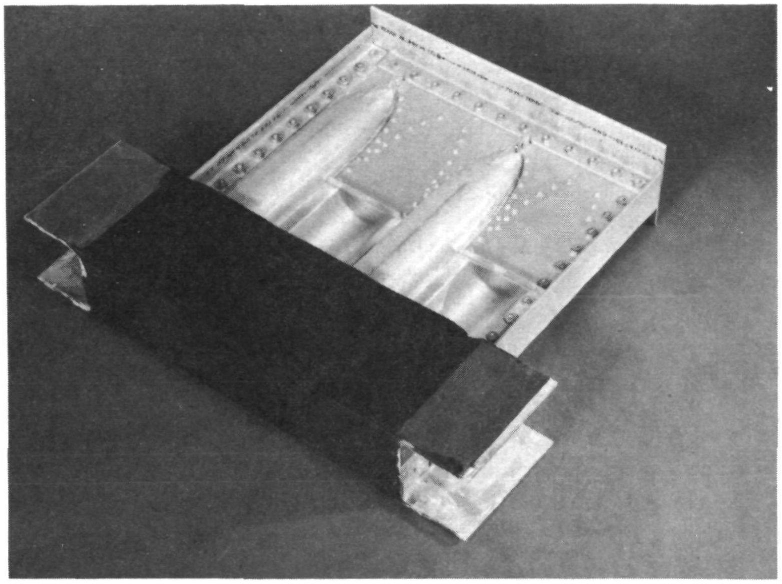


Figure 22-22: SINGLE SHEET END CLOSURE DEVELOPMENT SPECIMEN

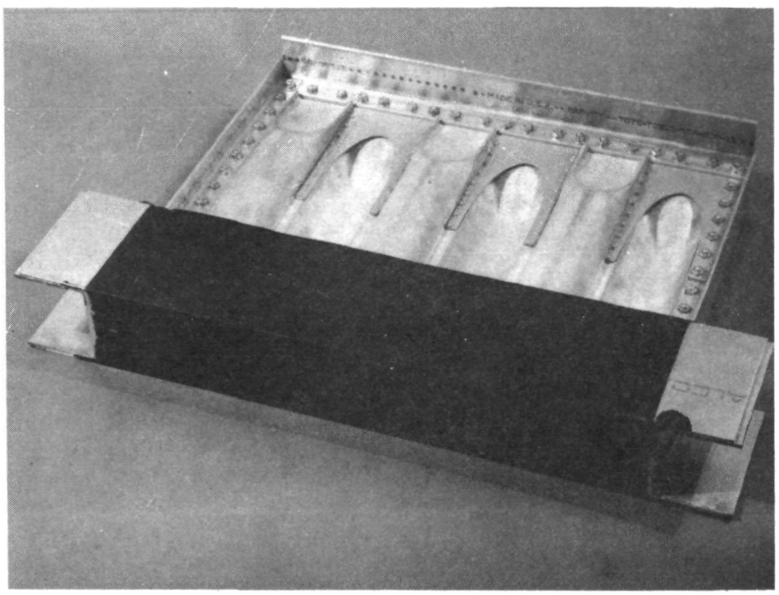


Figure 22-23: SINGLE SHEET END CLOSURE SHEAR TEST SPECIMEN

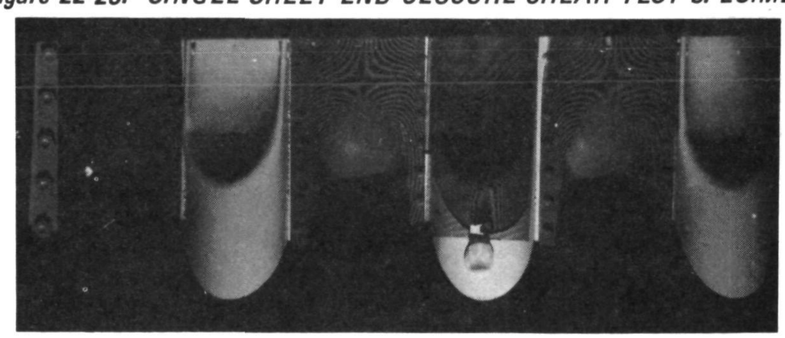


Figure 22-24: MOIRE PHOTOGRAPH OF SINGLE SHEET END CLOSURE LOADED IN SHEAR

single sheet specimens. The rotations observed in the single sheet specimens did not occur in the two sheet specimens since the couples induced in one of the two sheets oppose those in the other, as is evidenced by the bond failure in Figure 22-26.

The shear strength of the circular tube specimens of the initial screening test configuration was increased somewhat by addition of rivets in the area of the end closure. Figure 22-27 shows a portion of a specimen which was loaded in shear until the rivets failed in tension and tearing of the formed sheet occurred.

Figure 22-28 shows a specimen which is similar to that shown in Figure 22-27 except that external doublers were added in the area of the flats where the rivets were installed. As seen in the photograph this specimen failed by buckling of the tube wall in the end closure transition section. The failure load was very nearly equal to the shear strength of the corresponding uniform section tube specimens that were tested. Compression test specimens of the same design as that shown in Figure 22-28 failed by buckling in the uniform section. This type of failure indicated that the end closure was at least as strong as the uniform section for that specific design and could be used for the 40 x 40 inch panels.

The optimized panel cross section for the circular tube panels shown in Figure 21-1 was different than the cross section of the screening test configurations. Therefore new end closure forming dies had to be made, and it was possible to incorporate additional improvements in the design. Figure 22-29 shows a developmental part made from the improved circular tube end closure dies. This photograph shows the addition of a secondary bead in the area of the end closure. The secondary beads serve three basic functions. They stabilize the otherwise unsupported flats, they increase the moment of inertia at the end of the panel and they provide much better local configuration control. The bead end closure shown in Figure 22-29 was made slightly longer and therefore less abrupt than the previous circular tube end closures to provide a more gradual transition and thereby to reduce the stresses of the type that caused the bond peeling failure shown in Figure 22-26. The end closures of the design shown

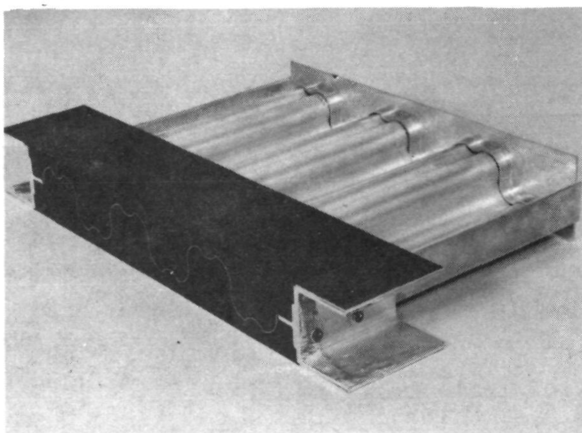


Figure 22-25: *FLUTED SINGLE SHEET END ATTACHMENT SHEAR TEST SPECIMEN*

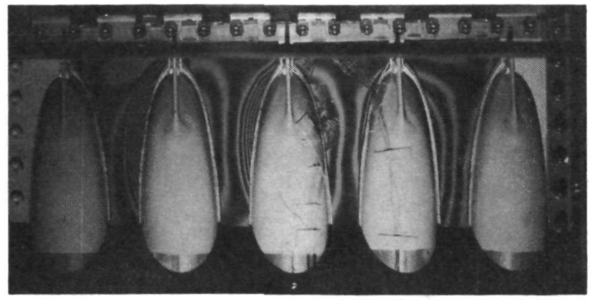


Figure 22-26: *MOIRE PHOTOGRAPH OF CIRCULAR TUBE END CLOSURE AFTER SHEAR LOAD INDUCED BOND FAILURE*

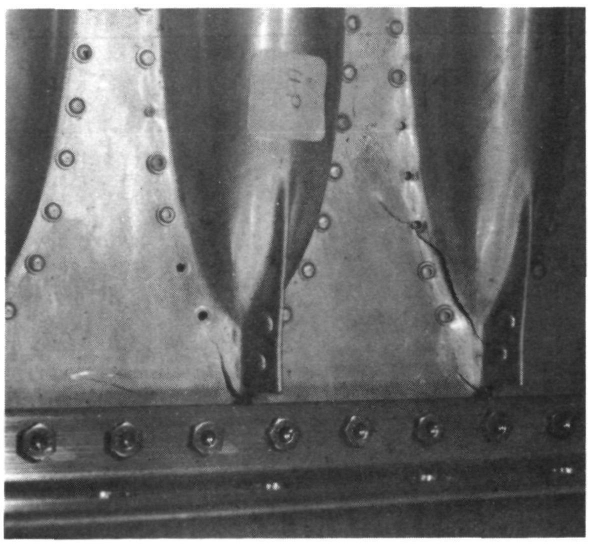


Figure 22-27: *CIRCULAR TUBE AFTER SHEAR LOAD INDUCED FAILURE*

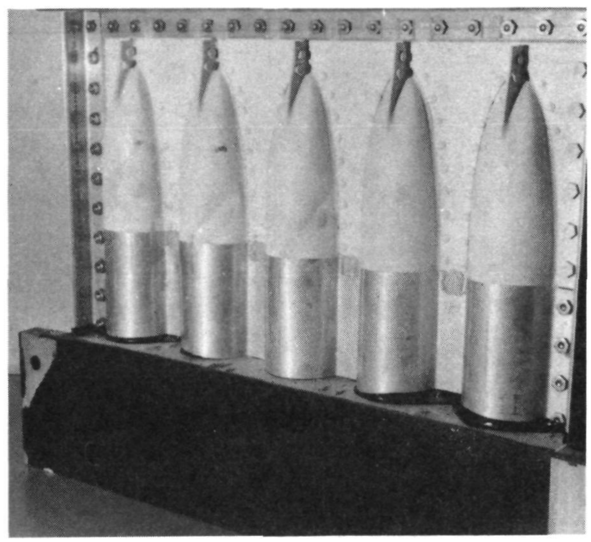


Figure 22-28: *TUBULAR SPECIMEN FAILED IN SHEAR*

in Figure 22-29 were used for the fabrication of the full sized test panels. The external doublers were not included in the end closure design for the full size panels since they were not designed for shear load alone. No separate end closure specimens of this design were tested.

22.2.3 End Closure Dies

As an exercise to determine versatility in the end closure forming tooling and to support the low load fluted tube development, the final circular tube end closure forming dies were modified and used to form demonstration specimens of an alternate design. The specimen shown in Figure 22-30 was formed with the modified tooling which is shown in Figures 22-31 and 22-32. Figure 22-31 shows the end closure reforming dies that were modified by removing the blade required to form the fins on the centerline of the bead. Figure 22-32 shows the secondary bead forming dies that were modified to take up the extra material that resulted from eliminating the fin on the bead. These dies are shown in use, before the modification, in Figures 9 and 10 of the summary document, Reference 7.

The contoured elements of the circular tube end closure die shown in Figure 22-31 were fabricated as follows. First the male part was machined from round bar stock and then it was used as a part of the mold to cast the plastic female die. Next the male part was chem milled to allow for the thickness of the formed part and attached to a base. The pins and secondary beads were sized to maintain a constant transverse developed length at all points along the end closure. The last steps required some trial and error detailing in order to obtain well shaped parts. However, the approach permitted rapid and economical development of the end closure dies.

22.2.4 Fluted Tube End Closures

The designs for the fluted tube end closures and the end closure forming dies were developed subsequent to those for the circular tube end closures. Consequently they duplicate many of the details of the circular tube end closures. The one significant difference was that the severe forming of the thinner sheets

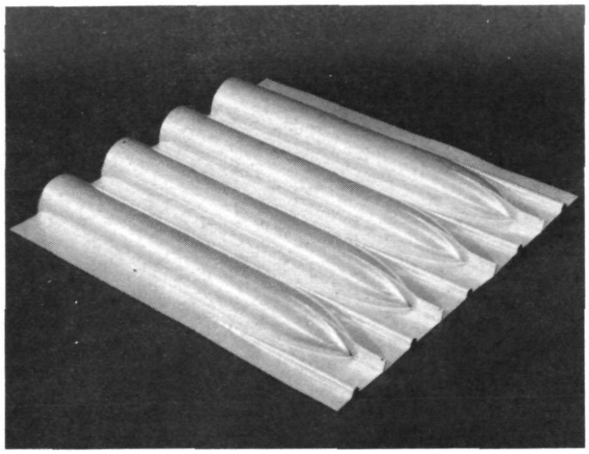


Figure 22-29: FINAL CIRCULAR TUBE END CLOSURE

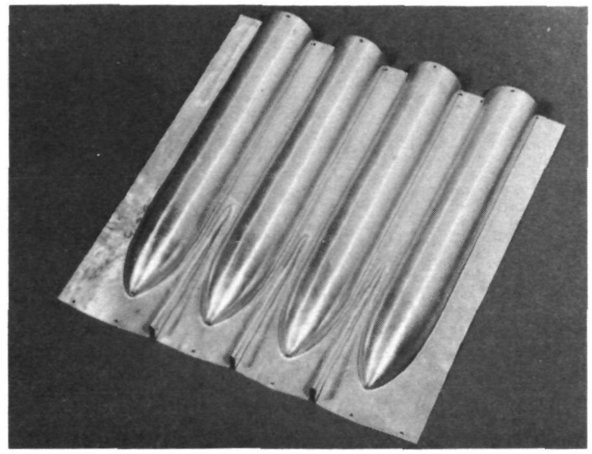


Figure 22-30: ALTERNATE CIRCULAR TUBE END CLOSURE

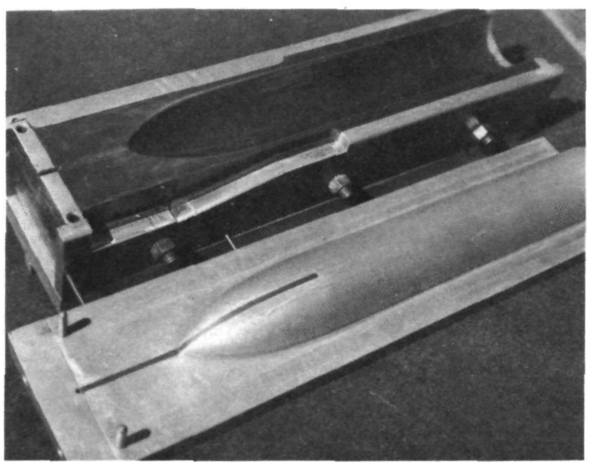


Figure 22-31: END CLOSURE REFORM DIES

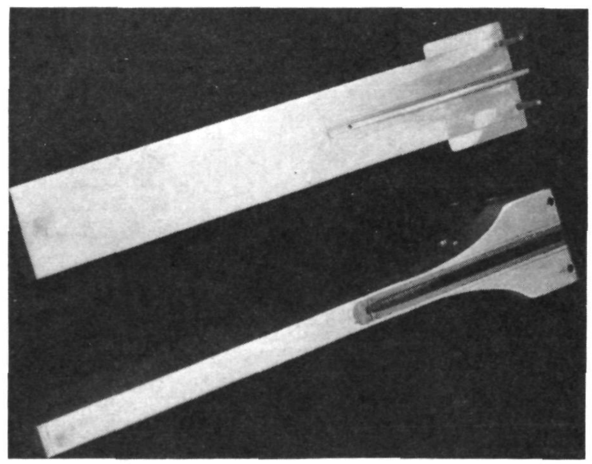


Figure 22-32: SECONDARY BEAD FORMING DIES

resulted in local wrinkling of the flats. Figure 22-33 shows one of the high load fluted tube end closure developmental parts with the wrinkles that existed after brake forming. The wrinkles were eliminated by a final high-energy rate electro-hydraulic sizing operation. Figure 22-34 shows a specimen which is relatively free of local wrinkles following final sizing. Figure 22-35 shows the end closure area of one of the high load fluted tube panels after bonding and riveting of fingered external doublers (needed in addition to the internal doubler for the high load design) but before preparation of the edges. Figure 22-36 shows an end closure specimen of that design that was failed by a combination of axial compression and shear at a load level well above the predicted strength for the full size test panels.

Figure 22-37 shows a low load fluted tube end closure test specimen that was failed in axial compression. This end closure configuration was selected to incorporate features similar to those shown in Figures 22-30 and 22-34. Figure 22-37 shows two small secondary beads that were used to prevent buckling in each of the large flat areas. As seen in Figure 22-37 the end closure specimen failures occurred in the uniform section rather than the end closure although no external doublers were used. Only a single fingered doubler of thickness equal to the face sheet thickness was used between the two face sheets. Individual and combined load tests were conducted to substantiate the adequacy of the two fluted tube end closure designs.

22.2.5 Electro-Hydraulic Forming

A sketch of the electro-hydraulic press is shown in Figure 22-38. The equipment used in the final sizing of the fluted tube end closures is shown in Figures 22-39 through 22-42. Figure 22-39 shows the electro-hydraulic press, the vacuum pump, the capacitor bank and the capacitor discharge control console. Figure 22-40 shows the female die for the fluted low load tube end closure installed in the press. Air bleed holes have been drilled and a vacuum line has been attached at the bottom of the die. Figure 22-41 shows the frame with a cutout for a single end closure, attached to the water chamber. The plastic dam above the cutout conforms to the part and prevents loss of water. Figure 22-42 shows one of the fluted low load tube panel faces being positioned for final sizing.

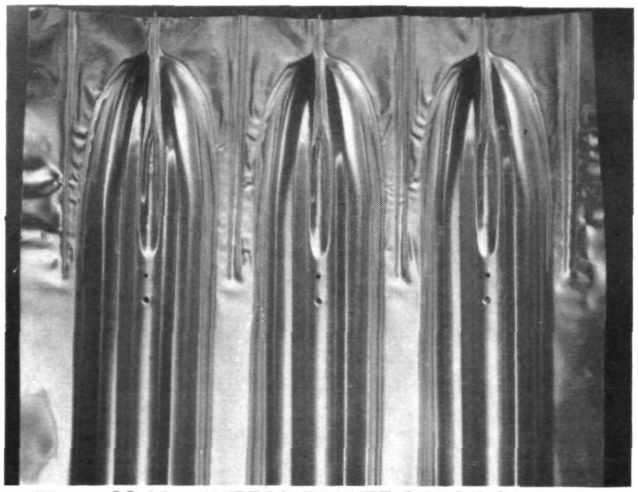


Figure 22-33: INTERMEDIATE STAGE 2A-2 END CLOSURE SHOWING FORMING WRINKLES

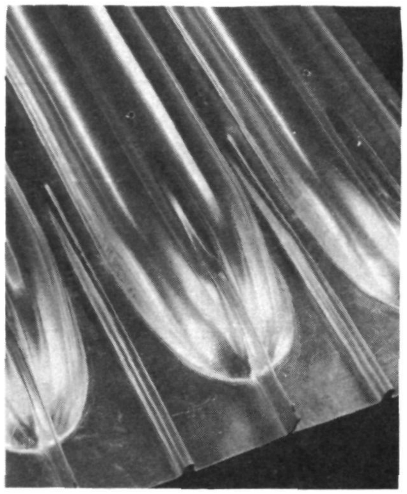


Figure 22-34: FINAL FLUTED TUBE END CLOSURE

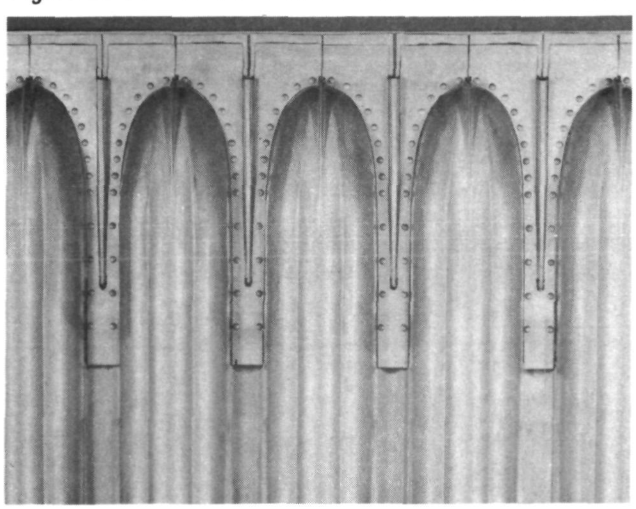


Figure 22-35: END CLOSURE WITH EXTERNAL DOUBLERS AND RIVETS

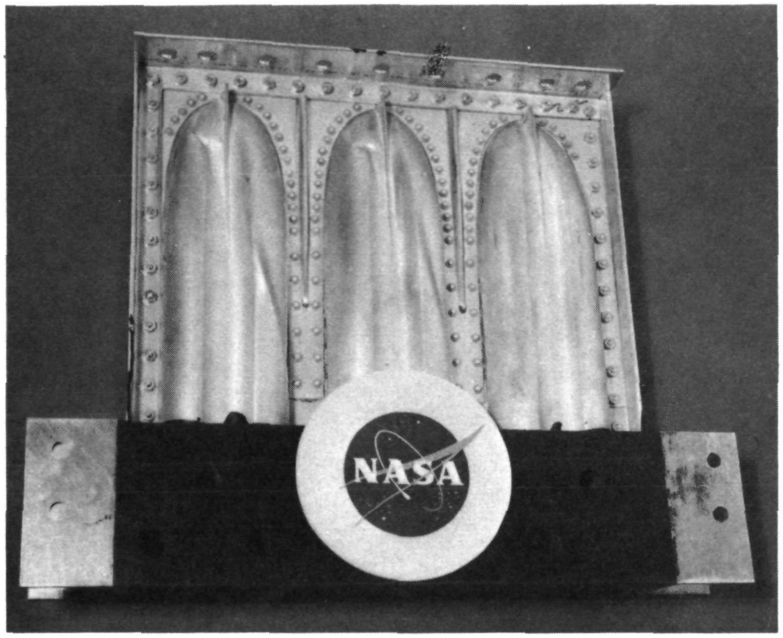


Figure 22-36: END CLOSURE SPECIMEN FAILED IN COMBINED AXIAL COMPRESSION AND SHEAR

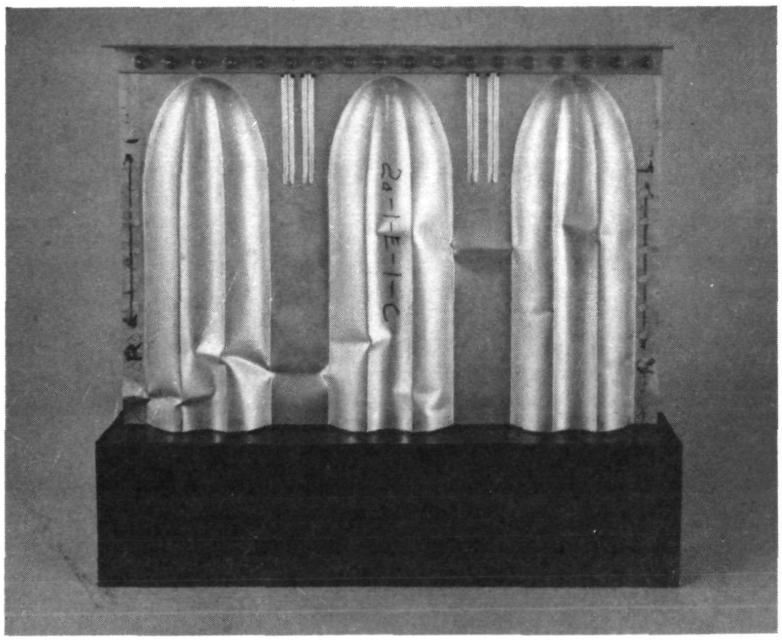
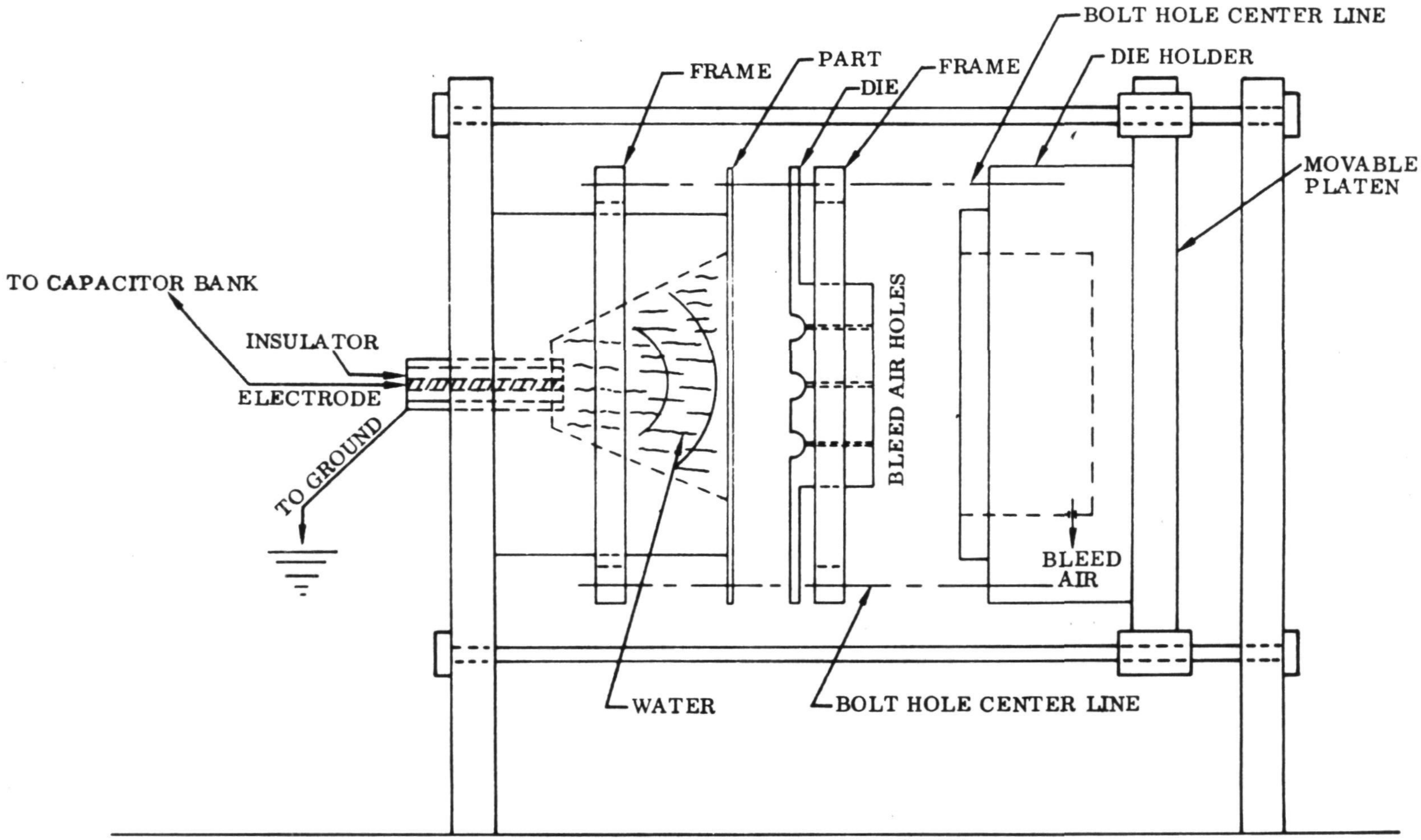


Figure 22-37: FAILED LOW LOAD FLUTED TUBE COMPRESSION SPECIMEN



SCHEMATIC (EXPLODED)

Figure 22- 38: ELECTRO-HYDRAULIC PRESS

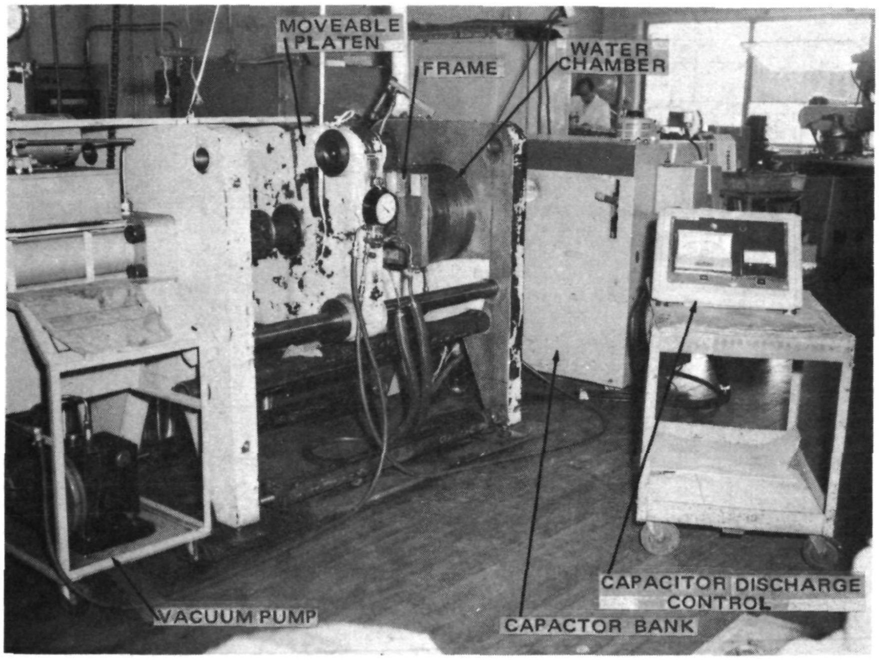


Figure 22-39 : ELECTRO-HYDRAULIC SYSTEM

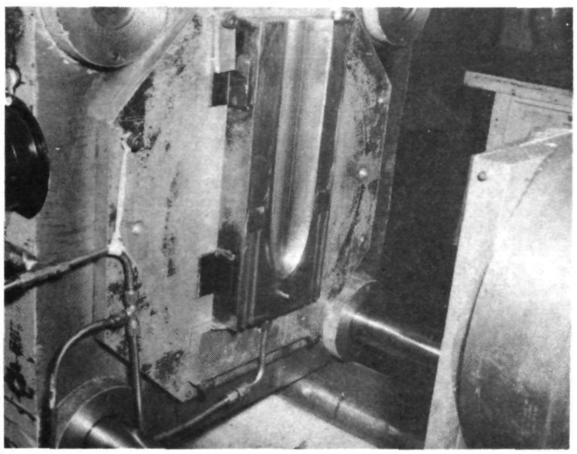


Figure 22-40 : END CLOSURE DIE MOUNTED IN ELECTRO-HYDRAULIC PRESS

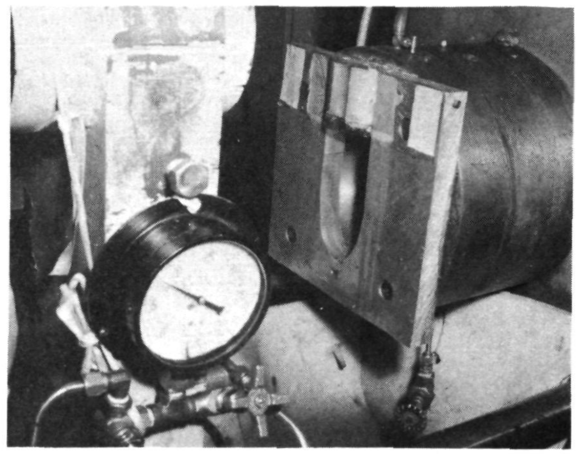


Figure 22-41 : FRAME WITH PLASTIC DAM TO ACCOMMODATE END CLOSURE

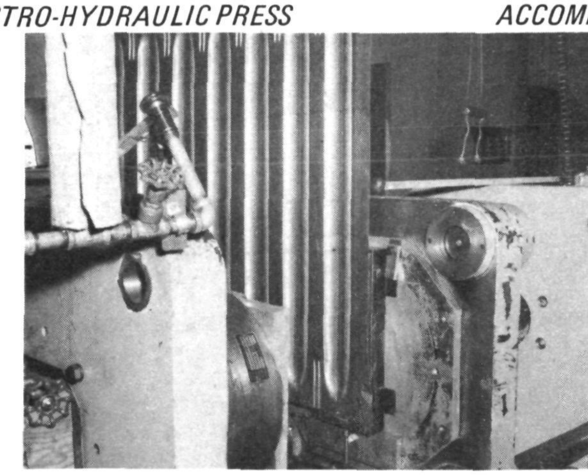


Figure 22-42 : PANEL IN POSITION FOR FINAL SIZING

Figures 22-33 and 22-34 show a fluted tube panel face before and after final sizing in the electro-hydraulic press.

22.3 Heat Treatment

The material for the formed parts was all obtained in the annealed condition and solution treated before forming for most of the test panels. Following the solution treatment the material was flattened by rolling. The material was then stored at reduced temperature until all forming was completed. Finally it was aged to the -T6 condition prior to assembly.

23.0 TEST SPECIMEN ASSEMBLY

The test specimens were all fabricated from 7075 aluminum. Therefore, the various fabrication and assembly techniques employed were those which are applicable to aluminum construction. Fabrication of the end closure test specimens is presented in Section 22.3. Details of the assembly of the local buckling specimens and the full size 40 x 40 inch panels are presented below.

23.1 Panel Test Specimens

The basic fabrication sequence applied to the full size 40 x 40 inch panel assemblies was as follows:

1) Shear to develop flat pattern width and length dimensions,

2) Numerical Control (NC) punch 0.125 inch diameter index holes (for locating on forming dies) and rectangular slots for fin and/or secondary bead trim,

3) Clean and solution heat-treat; hold in "W" condition at reduced temperature,

4) Roller flatten,

5) Brake form uniform cross-sections,

6) Reform end closures,

7) Degrease and artifically age to -T6 condition,

8) Fit-up for bonding (doublers and panels) and drill index holes for final bond cycle,

9) Clean for bonding (alkaline clean and deoxidize with sodium dichromate/sulphuric acid solution),

10) Wet rivet fins where applicable,

11) Assemble in fixture with bonding materials and bond,

12) Automatic rivet flat areas between end closures as required,

13) NC machine edge trim, attachment holes, fin and secondary bead edge margins,

14) Clean.

23.1.1 Circular Tube Panel Assembly

Forming of the 0.025 inch thick beaded circular tube panels is described in Section 22. Figure 23-1 shows one panel, an edge doubler and a fingered end doubler being prepared for bonding. Figure 23-2 shows the two panels, the edge doubler, the fingered end doubler and an external end doubler being prepared for bonding. The internal fingered doublers were scalloped slightly smaller than the inside mold line of the bead end closure. The end three inches of the doubler fingers were chem mill tapered from 0.025-inch to approximately 0.005-inch. The fingered doublers were required to provide shear continuity in the ends of the panels and to transmit the loads into the ends of the beads. The long narrow external doublers were required to provide increased bearing area for the mechanical fastener attachments at the edges of the panels.

The bonding materials consisted of the phenolic primer type I #EC-2320, a modified epoxy type II #AF-126, class I, grade 5 and a positioning fabric, produced by the 3M Company. The bonding was conducted per BAC Specification 5514. The autoclave cycle for these materials is one hour at 250°F with a bond line pressure of 25 to 100 psi.

Figure 23-3 shows a bonded panel with the bonding fixture. The straight elements of the bonding fixture were rectangular aluminum bars and the curved end members were cut from thick aluminum plate using a band saw.

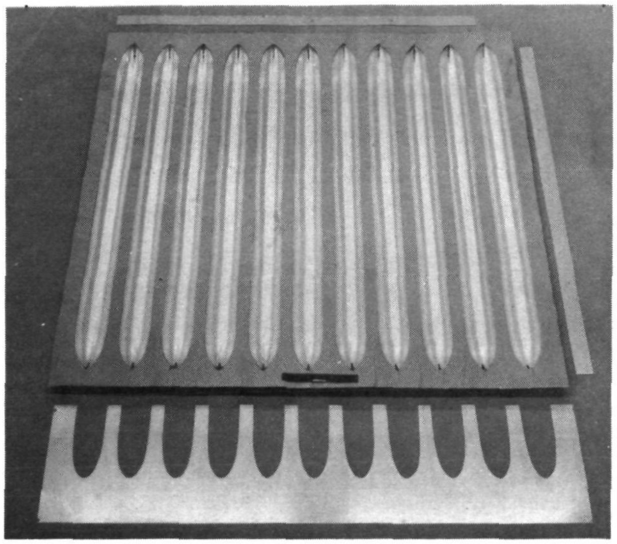


Figure 23-1: CIRCULAR TUBE ASSEMBLY BONDING LAY-UP

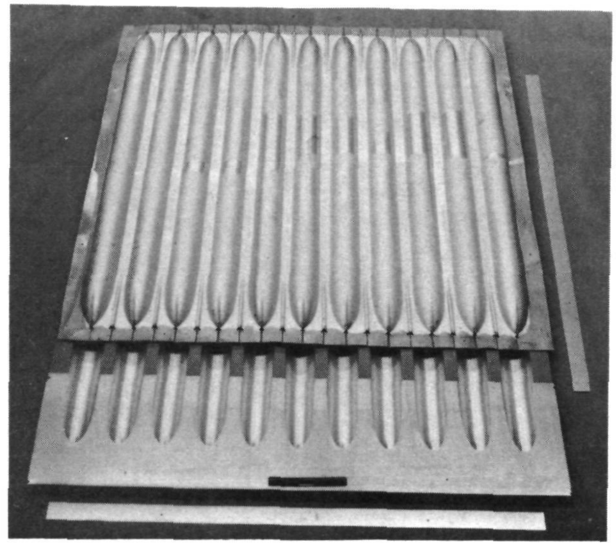


Figure 23-2: CIRCULAR TUBE ASSEMBLY BONDING LAY-UP

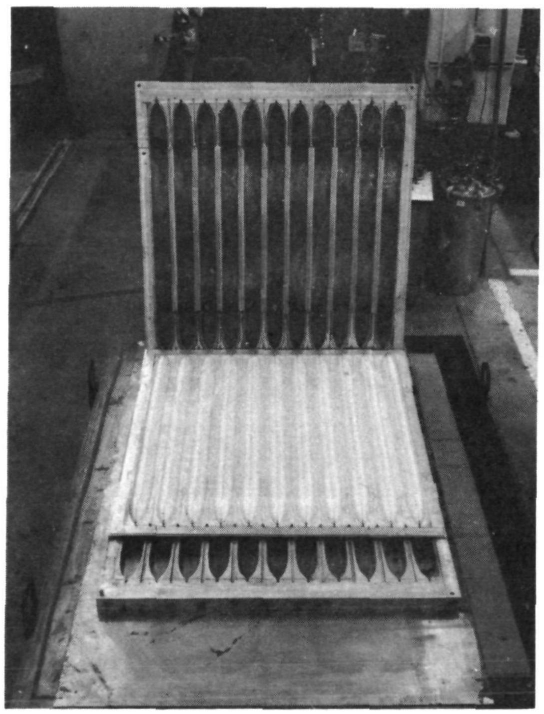


Figure 23-3: CIRCULAR TUBE PANEL WITH BONDING FIXTURE

23.1.2 High Load Fluted Tube Panel Assembly

Forming of the high load fluted tube panel faces was described in Section 22. The 0.020 inch thick high load fluted tube proved to be the most difficult design to produce end closures for without buckles in the flats. In this case it was found to be advantageous to solution heat-treat the panel faces after completing the forming including electro-hydraulic forming of the end closures. The heat treat cycle consisted of a 15 minute hot salt bath at 910° F to 930° F followed by an intermediate cold water quench. Artificial aging at 240° F to 260° F was then followed by air cooling.

Assembly of the high load fluted tube panels was essentially identical to the assembly of the circular tube panels. The only significant difference was that the high load fluted tube panels employed external fingered doublers whereas the circular tubular panels employed an internal fingered doubler only. The need for external doublers in addition to the internal doubler was determined from results of end closure tests. Figure 23-4 shows one of these panels after bonding and riveting but before NC edge preparation.

23.1.3 Low Load Fluted Tube Panel Assembly

The uniform cross-section of the low load fluted tube panel faces were formed with one set of developed brake form dies. The dies treated the three arcs and four mold lines simultaneously. In this case, the low arc angles and tangent points permitted application of the single action tooling. Some difficulty was encountered with the initial tool configurations near the end of the forming stroke. A partial trapping of the material resulted in a small amount of stretching which significantly reduced the springback.

Due to wrinkling problems associated with the reforming the 0.020 inch thick end closures the formed parts were electro-hydraulically sized as illustrated in Section 22.2.5. These parts were also solution heat-treated following the forming operations in a manner similar to that described for the high load fluted tube panels.

The assembly of the low load fluted panels was somewhat simpler than that for either of the other two tubular panel designs in that no fingered external doublers and no rivets were required. Otherwise the assembly was identical to that for the other tubular panels.

23.1.4 Fluted Single Sheet Panel Assembly

The fluted single sheet panels were formed using two sets of brake forming dies. The first set of dies developed an exaggerated sine wave configuration and the second set of dies formed the flutes and provided the final configuration. As a final brake operation, a standard brake was used to set the flat edge of the panel.

Figure 23-5 shows a completed single sheet test panel. The end members were not intended to represent flight hardware. They were designed for ease of fabrication and to permit testing of the panel section. The panel end plates shown in Figure 23-5 were machined from thick aluminum bar stock and grooved to receive the end of the corrugated panel as described in section 22.2.1.

The end plate assembly procedure consisted of bonding the corrugated sheet to the end plate. The bonding material was Hysol 5189/3538 which is a two part epoxy. The end plate and the epoxy were heated to $115^{\circ}F$ to improve flow characteristics, and epoxy was injected into the groove by use of a hypodermic. The corrugated sheet was manually inserted into the groove, starting at one end and progressively springing adjacent beads into the groove, and finally squaring the assembly on a horizontal surface plate with large angle blocks for the 24 hour room temperature cure cycle. The edge doublers were installed with the same epoxy as that used for the end plate attachment.

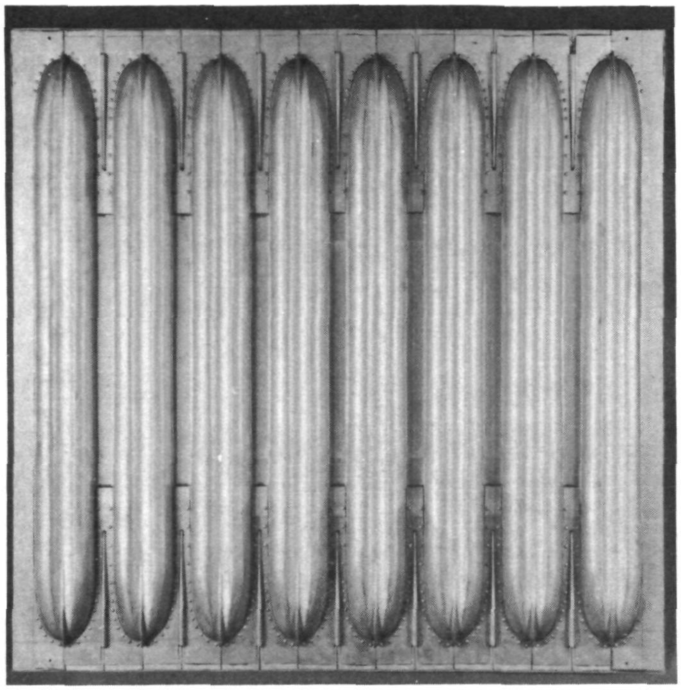


Figure 23-4: BONDED HIGH LOAD FLUTED TUBE PANEL

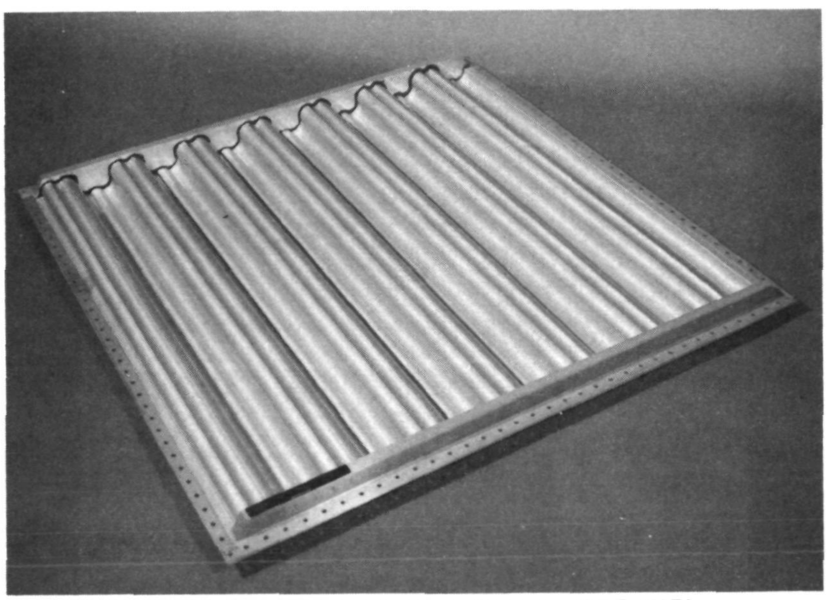


Figure 23-5: FLUTED SINGLE SHEET TEST PANEL

23.2 Local Buckling Specimens

Uniform section specimens of each of the panel designs were fabricated and prepared for testing before the full size 40 x 40 inch panels were fabricated. These specimens were typically formed using the brake forming dies and assembled using the same assembly techniques and bonding fixtures as those used with the full sized panels. These specimens were typically about 18 inches wide and had uniform test sections that were 10 inches long for the tubular specimens and 30 inches long for the single sheet specimens. The local buckling test specimen ends and edges were stabilized and provided with attachment as required for the various types of tests.

Figure 23-6 shows one of the low load fluted tube local buckling test specimens which was fabricated and tested under a combination of load conditions. Aluminum Tee section chords were bolted to each edge and channel section chord attachment members were bolted to the chords before potting. The ends of the specimen were potted using an epoxy tooling plastic with powdered metal filler. The potting stabilized the cross-section and permitted the specimen to be loaded in a local buckling test fixture. The specimen shown is typical of the tubular specimens except that the chords and chord attachment members were omitted from certain test specimens according to the required loading conditions. Figure 23-7 shows one of the fluted single sheet local buckling test specimens.

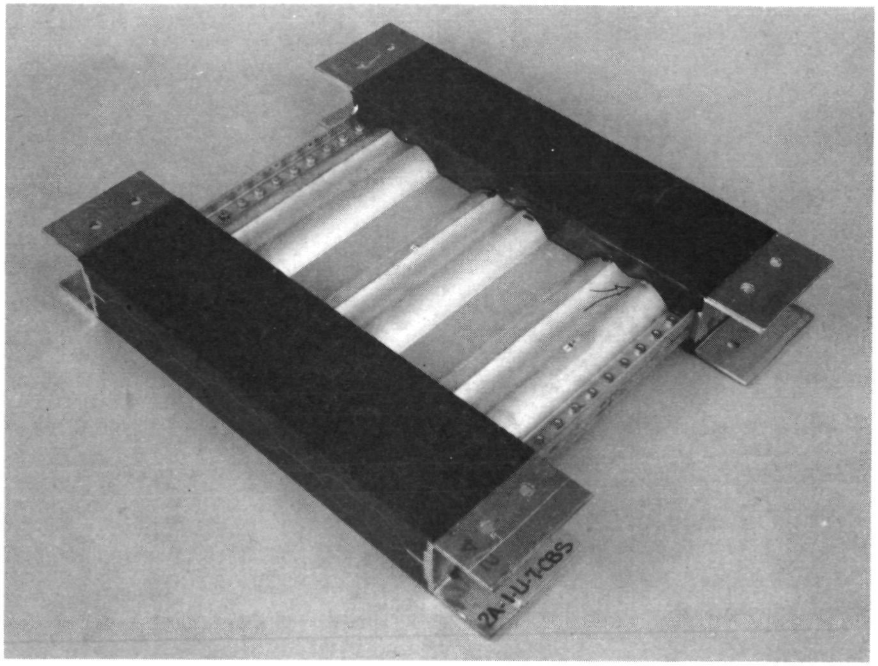


Figure 23-6: *LOW LOAD FLUTED TUBE LOCAL BUCKLING TEST SPECIMEN*

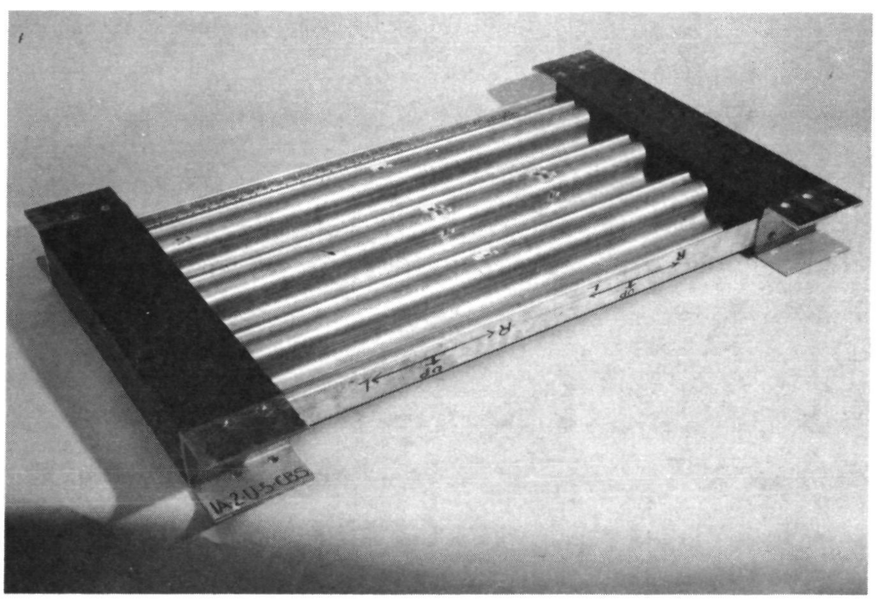


Figure 23-7 : *FLUTED SINGLE SHEET LOCAL BUCKLING SPECIMEN*

24.0 FLUTED TUBE PANEL MODIFICATIONS

Initial tests of the 40 x 40 inch fluted tube panels resulted in the decision to add reinforcement members in an attempt to stabilize the tube walls and improve the strength of the panels.

24.1 Low Load Design

After the initial tests, the first low load fluted panel, 2A-1-P-1, was modified by inserting machined rods as spacers and identified as 2A-1-P-1M. The purpose of the spacers was to prevent flattening of the beads.

Figures 24-1 and 24-2 show views of the modified panel. Figure 24-2 also shows one of the machined spacers lying in the flute of one of the beads. A mastic material was applied to the rounded end and the shoulder on the spacers to hold the spacers in place until loaded.

24.2 High Load Design

After initial testing the first of the high load fluted panels, 2A-2-P-1 was modified in a manner identical to that of panel 2A-1-P-1.

A portion of the second high load fluted tube panel assembly, 2A-2-P-2M is shown in Figure 24-3. The figure shows inserts which were riveted to the first beaded face sheet. The inserts were subsequently attached to the second face sheet by blind fasteners.

Figure 24-4 shows a portion of one face sheet of panel 2A-2-P-3M with inserts bonded in place. A dense potting material was placed between the formed inserts and the beaded sheet in areas where the applied pressure had not resulted in good contact. Following the potting, five mechanical fasteners were installed in each insert, locating two in each bead wall, and one in the flute.

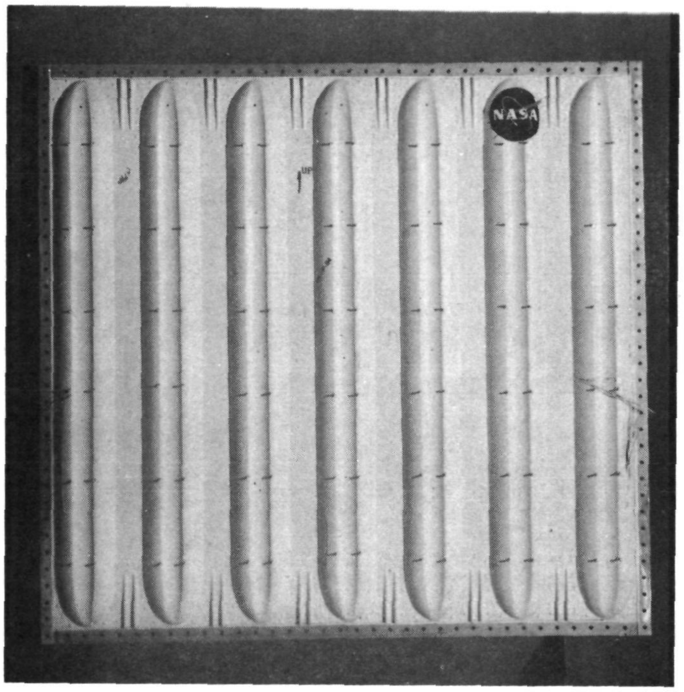


Figure 24-1: *PANEL 2A-1-P-1M*

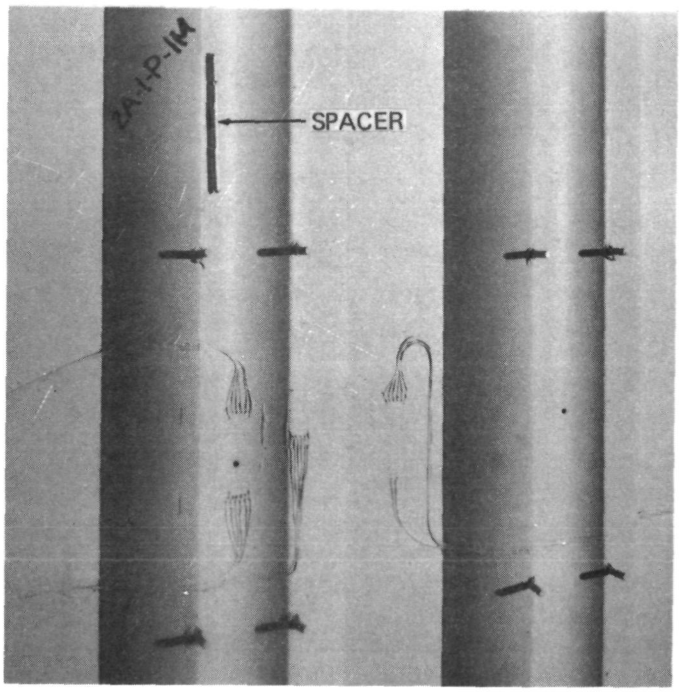


Figure 24-2: *PANEL 2A-1-P-1M AND MACHINED SPACER*

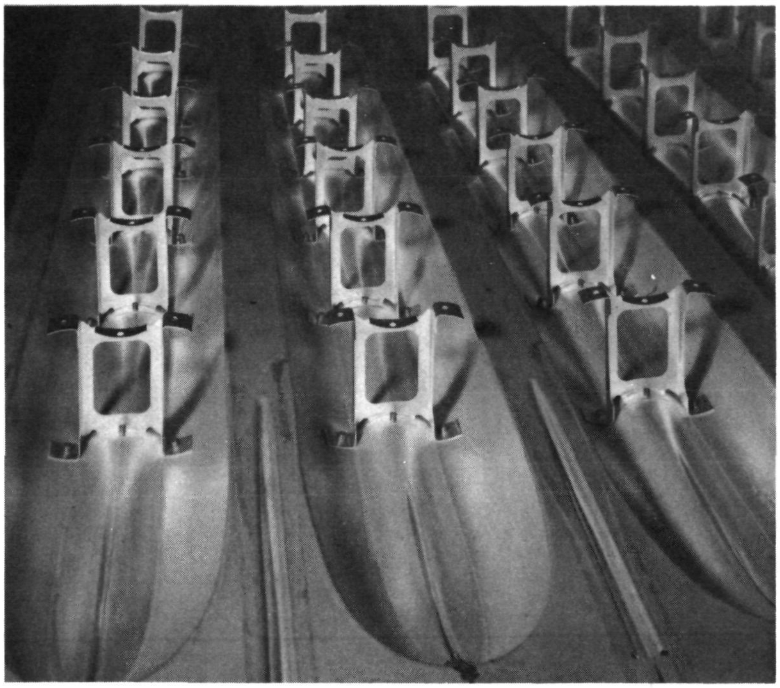


Figure 24-3: PANEL 2A-2-P-2M INSERTS

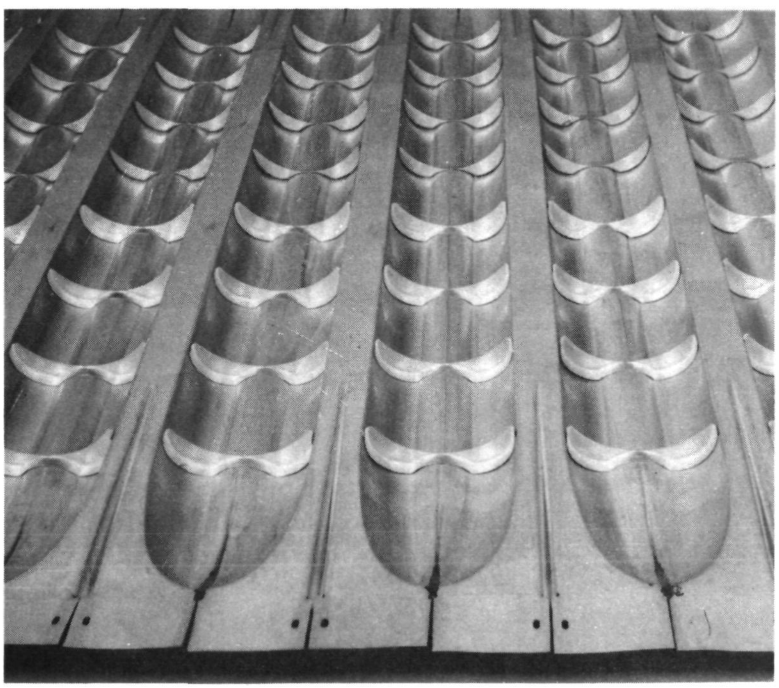


Figure 24-4: PANEL 2A-2-P-3M INSERTS

25.0 CONCLUDING REMARKS

The brake-forming fabrication techniques developed and applied on this program have proven to be practical and to produce structural panels with consistently high and predictable structural capabilities. These techniques provide a fabrication capability permitting a wide choice in configuration selection and result in finished parts that are virtually free from local material stretching or thinning. Thus the forming techniques developed on this program permit the analytically optimized bead configuration to be fabricated with virtually no material dependent limitations such as those that limit the configurations in trapped bead forming.

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